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ABSTRACT

Vacuum pumps have been described as compressors for rarefied gases. For more than twenty-five years the scroll compressor principle has been used in designing vacuum pumps that do not rely on oil to provide their pumping action. The dry scroll vacuum pump has been particularly successful as a source of rough vacuum for analytical instruments such as liquid-chromatography or gas-chromatography mass spectrometers. Such instruments are typically located in quiet laboratory environments where the scroll vacuum pump may be the only significant source of noise. Consequently, quiet operation is a key requirement of dry scroll vacuum pumps. This paper discusses an occurrence of stick-slip squeal that developed during the design of a new model, low noise, dry scroll pump. Stick-slip phenomena and the associated noise are the result of "self-excited" oscillations related to the difference between static and sliding friction. Rapidly oscillating friction forces occurring during a portion of the orbital cycle can result in induced vibration of the participating surfaces and structure, which radiate high-pitched noise.

In the case described, considerable effort was expended in developing a quiet pump design. However, a loud "chirping" noise found in a few late-stage prototypes caused a good deal of concern. It was necessary quickly to fully characterize the vibration behavior within the pump related to the noise and to develop design modifications to ensure that the noise was eliminated. The characteristics of the noise are described for the scroll pump along with the methods utilized to eliminate it from the design.

1. INTRODUCTION

1.1 Pump Observations

A dry scroll vacuum pump is typically fitted with tip seals in both the fixed and orbiting scrolls as shown in Fig. 1. The tip seals are designed to float in their grooves with little or no contact pressure between the mating surfaces. Due to manufacturing tolerances and thermal expansion in operation, one or both seals can be compressed between the bottom of the groove and the mating surface. The seals are a firm (thermoplastic) material, so a small variation in axial dimensions can cause a large variation in contact (normal) force.

The noise that caused this investigation was usually characterized as a "chirp". The noise was heard as a high pitched noise delivered in rapid pulses (one or two per revolution, at 1500-1800 rpm). It was observed early on that the noise occurred more often with new seals before they were worn in. Once worn in the noise occurred less often. Furthermore, changing the cooling fan speed would often eliminate the chirp noise. Based on the investigation, it was determined that the most likely cause of the noise was stick-slip motion between the tip seal and its mating surface.

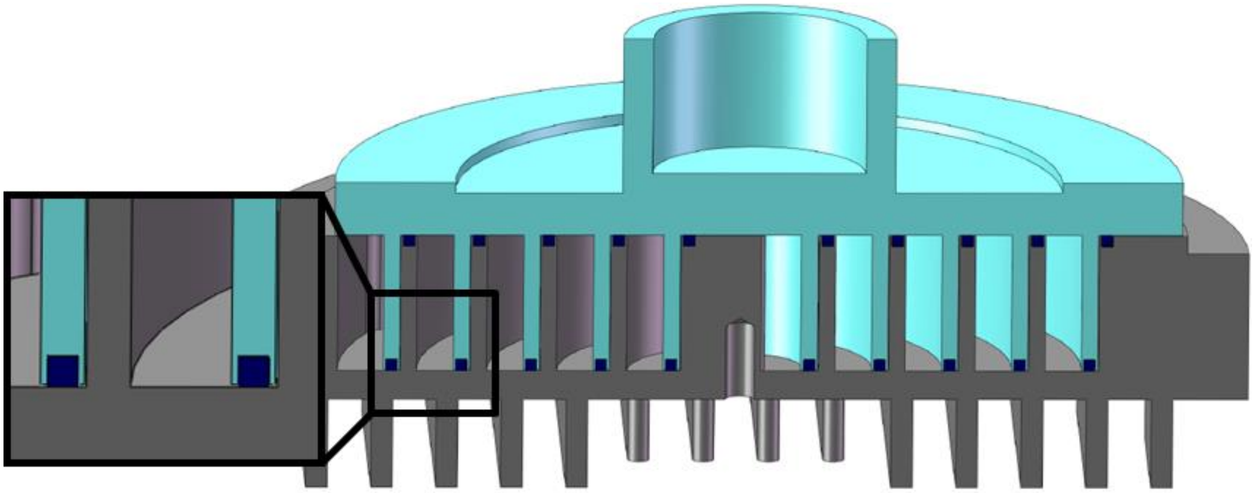


Figure 1: Longitudinal section view of scrolls and tip seals in working position

1.2 Theory of the Noise

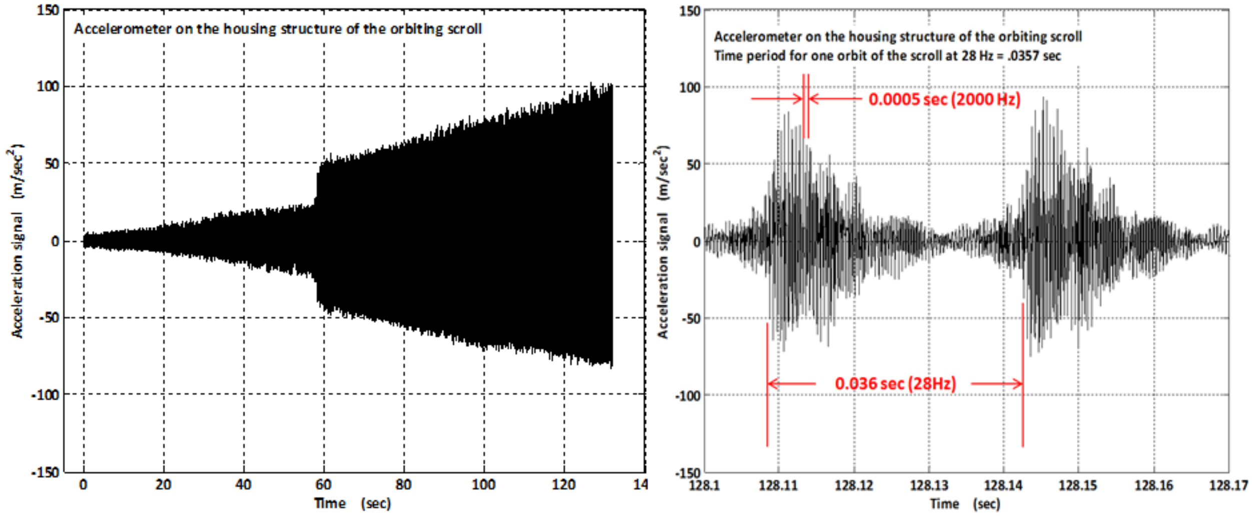
Stick-slip motion can occur, if the conditions of normal force and relative velocity are right, when the tip of the vane-seal assembly becomes momentarily fixed - due to static friction - relative to the base plate. As the motion of the orbiting vane continues, the deformation of the vane increases to the point that the internal forces of deformation in the vane are sufficient to overcome static friction and the vane releases, resulting in a drop in friction force which is now governed by the lesser coefficient of sliding friction. Because more energy is built up in static deflection than is dissipated in sliding motion, the resonant response of the vane builds until there is significant vibration transmission to the external surfaces of the pump.

It is believed that the stick-slip motion occurs during the circular orbit when the relative motion is substantially perpendicular to the vane. The stick-slip motion excites vibration resonances within the vane, of a frequency much higher than the rotational frequency of the mechanism. These resonances primarily involve flexural motion perpendicular to the vane surface. This behavior should happen to a greater extent at the outer turns of the spiral vane because its curvature is less there and the vane is less stiff in flexure than in the inner turns. The flexural motion should be greatest at the vane tip. During the part of the orbital cycle where the relative motion is along the vane, only sliding motion without stick-slip oscillation occurs and the friction forces act to dissipate vibration energy in the vane. As a result, the high frequency vibration and noise occur as a series of pulses rather than a continuous tone, resulting in the description of the noise as "chirping".

We were able to start and stop the phenomenon at will, and to study the onset of the noise, by varying the cooling airflow and thus the component temperatures. It is assumed that differential thermal expansion of the various pump components results in changes in contact pressure between the seals and base plates.

2. MEASUREMENTS AND NOISE CHARACTERISTICS

Figure 2a is a time plot of vibration of the orbiting scroll housing as measured by an accelerometer. This figure shows the development of the chirping noise, as seen in the vibration time signal, versus time, over an approximately 2.5 minute period. Before the start of the plot, the pump is running without noticeable noise and with the cooling fan turned off. When the cooling fan is turned on and the pump components begin to cool unevenly, the signal begins to grow due to the chirping noise; then a sudden increase or jump occurs, followed by a steeper growth in the amplitude. Eventually the vibration and noise level out to a steady state, though this is not shown on the plot. Figure 2b shows a 0.07 sec duration time slice of the same vibration signal, after the chirping noise is well established. Note that pulses, approx. 0.01 sec. long, occur every 0.036 sec. which is the rotational time period of the pump/scroll at 1680 rpm or 28 Hz. The content of each pulse is a tone whose fundamental component is centered around 2000 Hz.



(a) **(b)**

Figure 2: Housing acceleration signal: (a) showing evolution of "chirping" noise; (b) 0.07 sec. time slice showing the noise/vibration when well established

Fig. 2c is a noise spectrum of the pump with the noise well established, showing broad peaks at 2000 Hz and multiples of 2000 Hz.

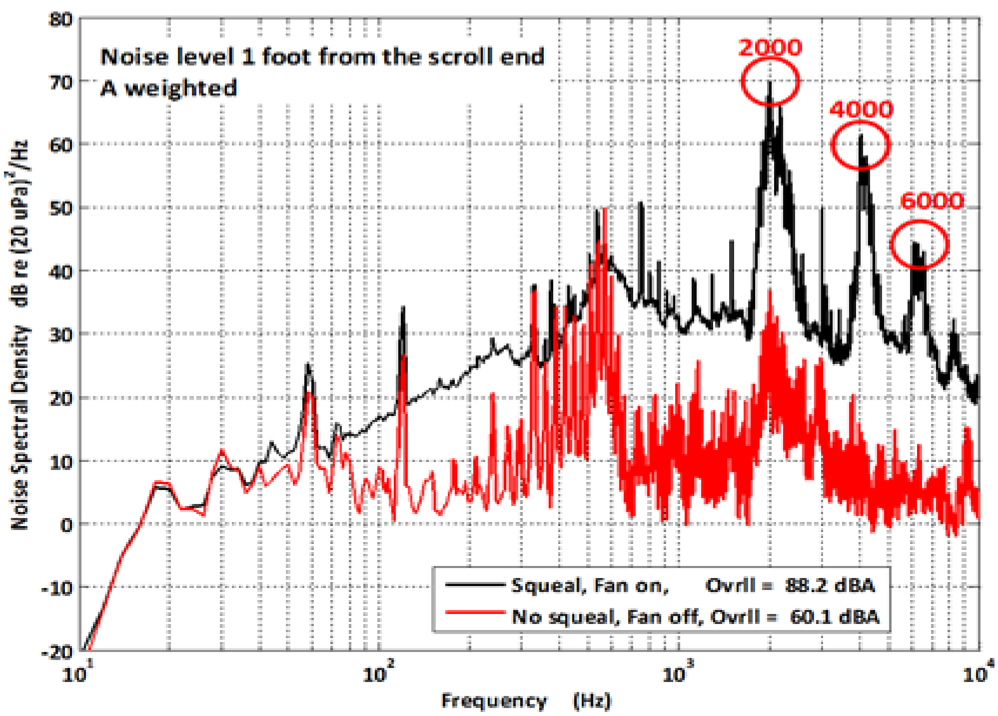
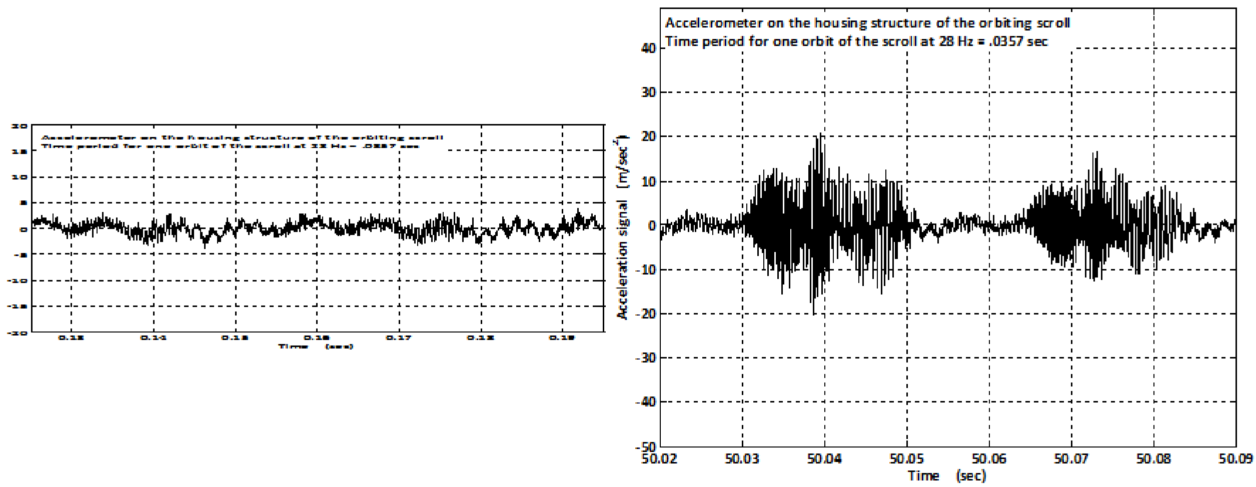


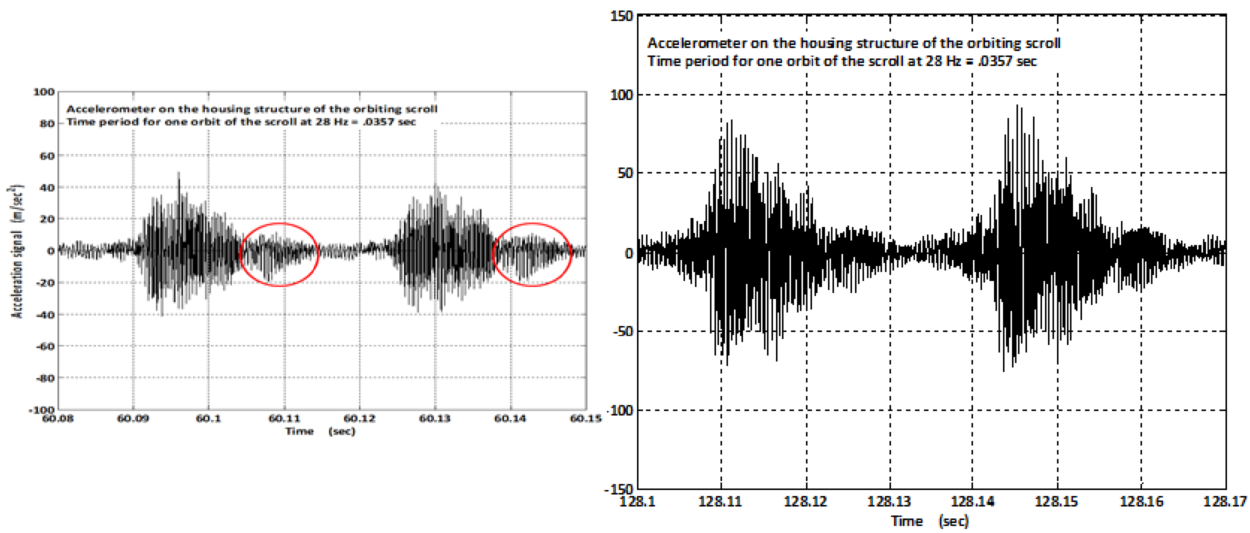
Figure 2c: Audible spectrum with and without "chirping" noise

Figures 2d-g show shorter slices during the initial increase in amplitude as the chirping noise develops, but before the sudden increase in amplitude. (The y axis range of 2d, 2e is different than that of 2f, 2g).



(d) **(e)**

Figure 2 (cont'd): Housing accceleration signal, short time slices: d) just before "chirping" noise became noticeable; e) just before the sudden jump in amplitude



(f) **(g)**

Figure 2 (cont'd): Housing acceleration signal, short time slices: (f) after the sudden jump in amplitude - red circles indicate a possible second pulse; (g) near the end of the plot in Fig. 2a

We did not have a position marker to relate the timing of the pulses to the actual position of the orbiting scroll, but the results do imply that the pulse of noise occurs primarily during one direction of relative motion and less intensely (if at all) during the other direction of relative motion. (In Figure 2f the red ovals indicate a possible, smaller, second disturbance at 180 degrees orbital position from the main pulse.) Due to manufacturing tolerances in the pump drivetrain, the movement of the orbiting scroll will not be perfectly parallel to the surfaces of the fixed scroll, thus the contact force is likely to generate stick-slip behavior at only one point in the orbiting path.

Figure 2h shows a different vibration measurement on the same pump over many rotations of the orbiting scroll. An interesting pattern was observed in that the pulses appear to come in groups of approximately four pulses; the first in the group has the largest amplitude and the subsequent pulses in the group have decreasing amplitude, until a pulse with large amplitude occurs again. The number of pulses in a group was not consistent: generally four pulses to a group, but groups were observed with three to seven pulses. This pattern wasn't always seen during retesting of the same pump and the behavior remains unexplained.

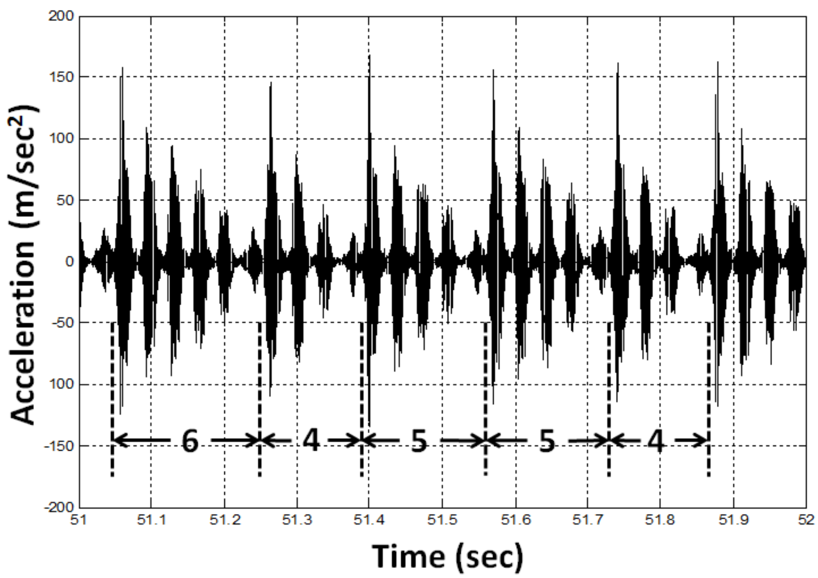
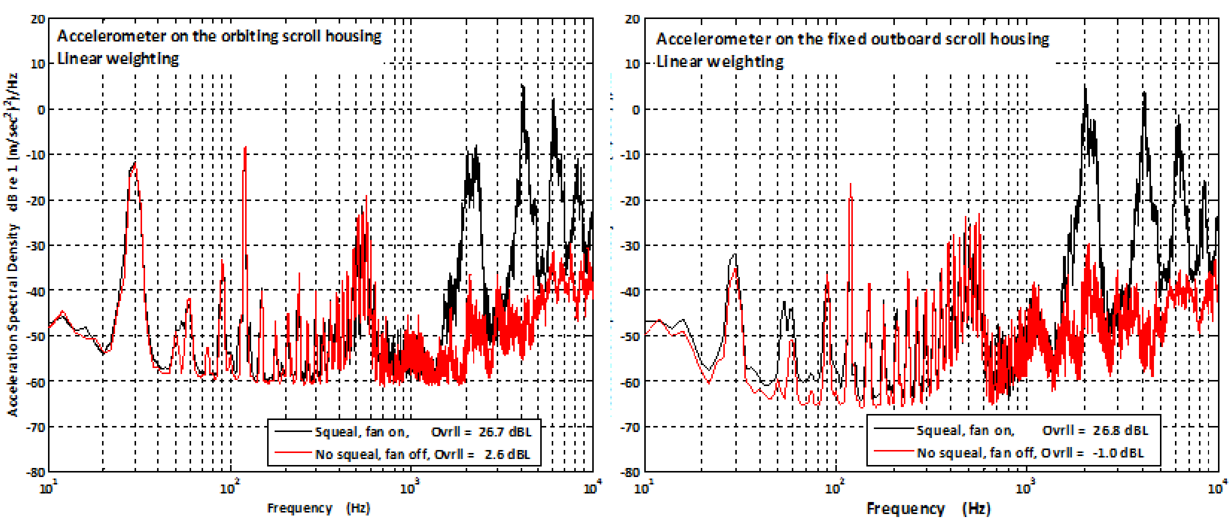


Figure 2h: Longer time slice of acceleration for same unit; note varying numbers of pulses between large pulses

3. NOISE AND VIBRATION SPECTRA

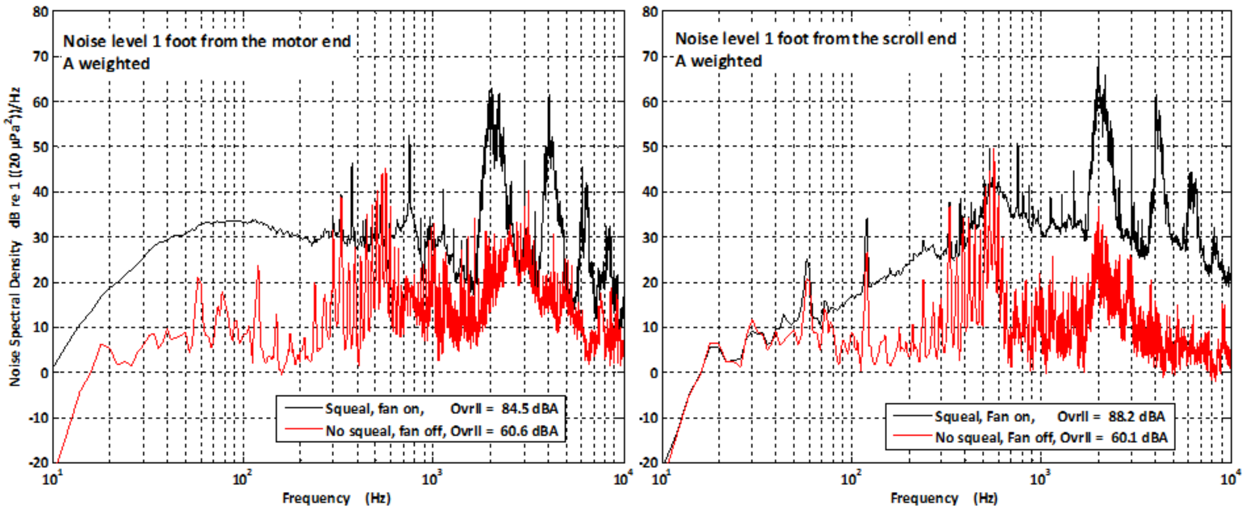
Narrowband vibration spectra are shown in Figures 3a, b for measurement locations on the orbiting scroll and fixed scroll housings. Curves are shown during steady chirping with the cooling fan on, and with the fan off and no noise. During the chirping noise there were significant bands of high vibration near 2, 4, 6 and 8 kHz that are harmonically related. The bands do not correspond to fixed sinusoids at a single frequency but are broad, likely corresponding to a changing frequency during the part of the orbit when squeal occurs. Other vibration peaks at lower frequencies were relatively consistent with the fan on or off, i.e. with squeal or no squeal, respectively. These likely correspond to the fundamental and harmonics related to the rotation of the motor. The overall linear weighted vibration levels were nearly 25dB greater during squeal.



(a) **(b)**

Figure 3: Acceleration spectra of (a) orbiting scroll housing; (b) fixed scroll housing: "chirping" noise vs. no noise.

Noise spectra are shown in Figures 4a, b for microphone locations approximately 1 foot from the scroll and motor ends of the pump. The harmonically related bands are again seen in the noise at higher frequencies where the overall A weighted noise levels were also greater by nearly 25 dBA with chirping noise (fan on) than without chirping noise (fan off). At the motor end of the unit, Figure 4a, the larger broad spectrum levels at low frequencies were due to wind noise as the microphone was positioned within the cooling airflow.



(a) **(b)**

Figure 4: Noise spectra from (a) scroll end; (b) motor end: "chirping" noise vs. no noise.

4. RESONANT MODES OF THE SCROLL ASSEMBLIES

The conjecture is that the chirping noise is related to an oscillation of the vane that occurs primarily at the outer end of the vane with greatest motion at the seal edge furthest from the base plate. This motion is driven by fluctuating friction forces during the stick-slip process and excites resonances in the scroll assemblies that are dominated by motion of the vanes.

To investigate the resonant behavior of the vanes, an impulsive force was applied with an impact hammer to the end of the orbiting scroll vane at the outer turn, this being the location where the vane is least stiff in flexure. The impact was applied at the top of the vane near the tip seal. A small, lightweight, 0.5 gm accelerometer was attached to the vane at the same location and a microphone was placed approximately one inch from the vane near the impact point. Transfer function results from force to vane acceleration (m/sec^2/N) and noise (20 µPa/N) are shown in Figure 5. For these tests the fixed outboard scroll housing was removed in order to access the orbiting scroll. The intent was to identify whether there was significant resonant activity in the vane in the primary frequency where chirping noise occurs, *i.e.*, near 2 kHz.

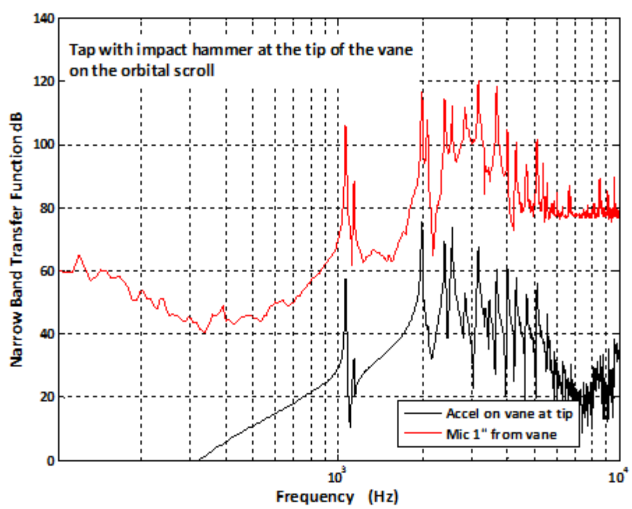


Figure 5: Transfer function from impulsive force to scroll vane

The first resonance occurs near 1 kHz and is characterized, based on finite element models, by the motion of the orbital scroll assembly on its support relative to the pump shaft. Resonances that involve significant motion of the vane relative to the base plate structure occur starting near 2 kHz, consistent with the primary noise frequency. Fig. 6 shows an FEA result, a vibrational mode of the orbiting scroll with natural frequency near 2000 Hz. FEA also indicated vibrational modes in the fixed scroll structure with natural frequencies near 2000 Hz as shown in Fig. 7.

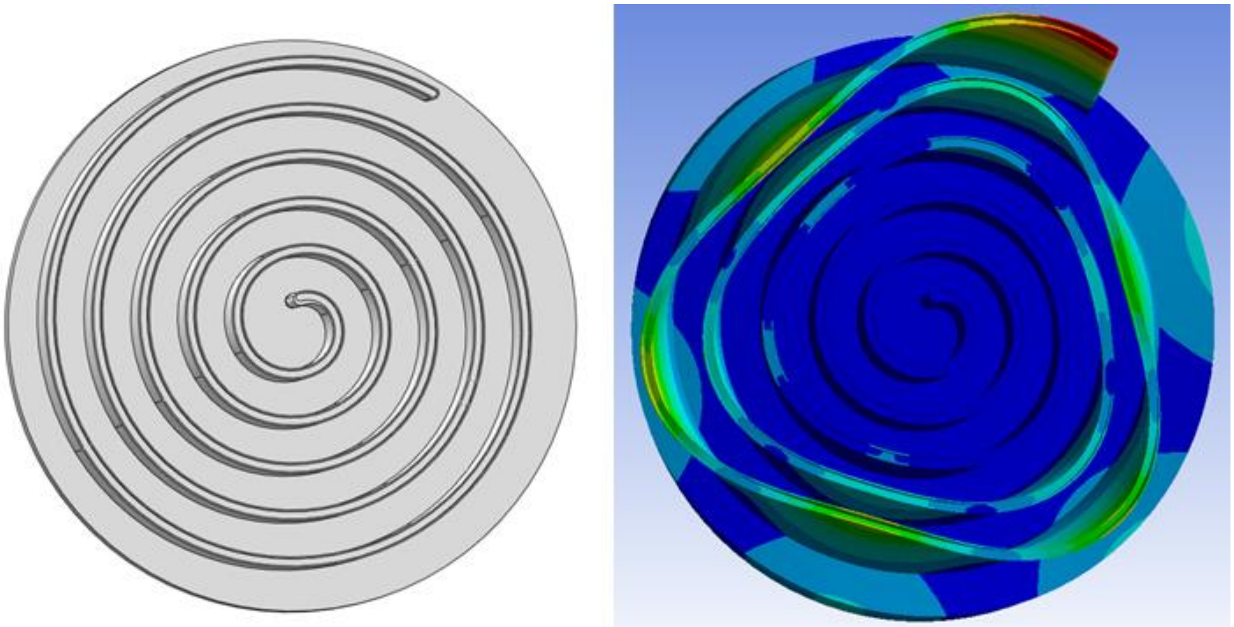


Figure 6: Typical deflection mode near 2000 Hz for orbiting scroll

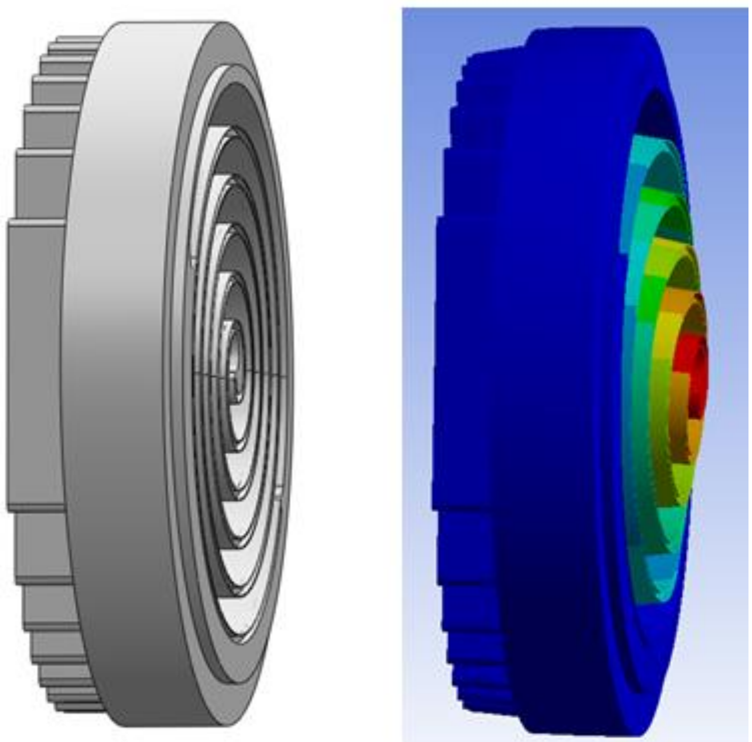


Figure 7: Typical deflection mode near 2000 Hz for fixed scroll

The stick-slip behavior ***seeks*** out resonant behavior within the mechanical system that involves an interaction between contacting parts with sliding friction to establish the stick-slip oscillation. It is not simply an excitation at a particular frequency based on external factors. The frequency of the stick-slip oscillation doesn't simply match the resonance frequency of the individual component alone, as the contact condition between the mating surfaces is at times during the oscillation fixed and at other times sliding. This establishes a limit cycle behavior with a more complicated relationship between the primary stick-slip frequency and the frequency of the mechanical resonance and also the generation of significant harmonic content in the oscillation. It is believed that the stepwise increase in amplitude of the vibration signal, seen in Fig. 2a, may be caused by a sudden large increase in the resonant response of the fixed scroll and its structure to the motion of the orbiting scroll..

5. MITIGATION OF THE NOISE

As described above, the stick-slip phenomenon requires a certain normal force applied between the surfaces of concern. If the dimensions of the tip seal and its groove are chosen so that there is always axial clearance between the top surface of the tip seal and the mating surface, the normal force cannot reach the level needed to induce the stick-slip mechanism. Based on the finite element analysis of orbiting scroll vibrational modes, described above, and the expectation that the scroll vane is most flexible near the periphery, it was determined to alter the detail design of the scrolls to increase axial clearance of the tip seal in the outermost portion of the vane. It was hoped that, even if rigid axial contact between the tip seal and its mating surface were to occur, it would occur near the center of the scroll, and that the higher vane stiffness near the center would prevent the stick-slip noise. The validation testing described below would thus also serve as confirmation of the location of the problem.

Validation of the changes consisted of building a number of pumps, with the new design and a variety of tolerance stacks, and monitoring using accelerometers and vibration monitoring software to detect whether the vibration characteristic of the "chirp" noise was detected. One pump did experience the vibration. Upon investigation it turned out that this unit had been machined out of tolerance, *i.e*., to the old dimensions. No units with the corrective action properly applied experienced the vibration or noise of concern.

6. CONCLUSIONS

Machinery designers should take note that wherever sliding contact occurs between components that are relatively rigid in the normal direction and relatively elastic in a direction parallel to the motion, there is a risk of stick-slip noise. In addition, such noises may not be present on all units, as small variations in normal force or sliding speed can cause the noise to appear or disappear. This should be taken into account especially in design of low-noise products.

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